

FUNDAMENTAL PHYSICS IN OBSERVATIONAL COSMOLOGY

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Abstract. I discuss, through a few examples, how observational cosmology can provide insights on hypothetical fundamental physics phenomena or mechanisms, such as Grand Unified Theory, Superstring alternatives to the inflation paradigm, and inflation itself.

Keywords: Grand Unified Theory, Superstring Theory, Inflation, Bouncing cosmological models.

1 Introduction

Cosmology has definitely entered a phase of precision measurements: Cosmic Microwave Background (CMB) anisotropies (Komatsu 2010), Large Scale Structure (LSS) observations (Abazajian et al. 2009) and the magnitude-redshift distribution of Supernovæ Ia (Amanullah et al. 2009) to name the most prominent, have radically transformed the field. Forthcoming experiments (e.g. Planck) and new data such as Baryonic Acoustic Oscillations (Percival et al. 2009) or those based on the 21 cm transition (Furlanetto et al. 2006) will further change our view of primordial cosmology (Peter and Uzan 2009). It is no longer enough to try and roughly understand cosmological observations: time has come to use these data in a new way instead of merely gather them.

One such way is to test inflationary predictions in greater details to decide which version is the most satisfactory, and hence to know how it should be implemented in a high energy physics scheme, in particular in a string theory framework; I present in Sec. 2 a specific example based on the reheating temperature (Martin & Ringeval 2010). Another way consists in evaluating directly some consequences of high energy models such as Grand Unified Theories (GUT); for this, I concentrate (Sec. 3) on the still possible fraction of topological defects as active seeds for CMB fluctuations (Bouchet et al. 2002; Fraisse et al. 2008; Pogossian et al. 2009). Finally, taking the special case of bouncing cosmology (Sec. 4), I argue that challengers to inflation may still be worth investigating, both at the theoretical and observational levels (Peter & Pinto-Neto 2008).

2 Inflation

Inflation (Martin 2008) is nowadays the most widely accepted solution to the old puzzles of standard cosmology. Its basic predictions concern the background itself (e.g., the ratio of the total density ρ_{tot} to the critical density ρ_{crit} , Ω that is expected to be unity to an amazing precision, leading to a vanishing curvature $\Omega = 1 \iff \mathcal{K} = 0$) as well as its perturbations that have acted as primordial seeds for the formation of the now observed LSS. These perturbations imprinted the CMB in a way that must be correlated with LSS: a consistent model should explain both sets of data.

Inflation is modeled by a scalar field slowly rolling in a potential. A few parameters of this potential allow for an almost complete fit of the whole available set of data; in fact, it is often argued that only the slow-roll phase is probed by astrophysical observations; this phase requires the scalar field to be far from its equilibrium value. In itself, this is already quite an achievement, and a way to discriminate between various models.

The degree of accuracy of the most recent data has now increased to a such a level that it has become possible to probe the different part of the potential corresponding to reheating, i.e. the transition between the end of inflation itself and the radiation dominated era, at a time for which the scalar field is therefore close to

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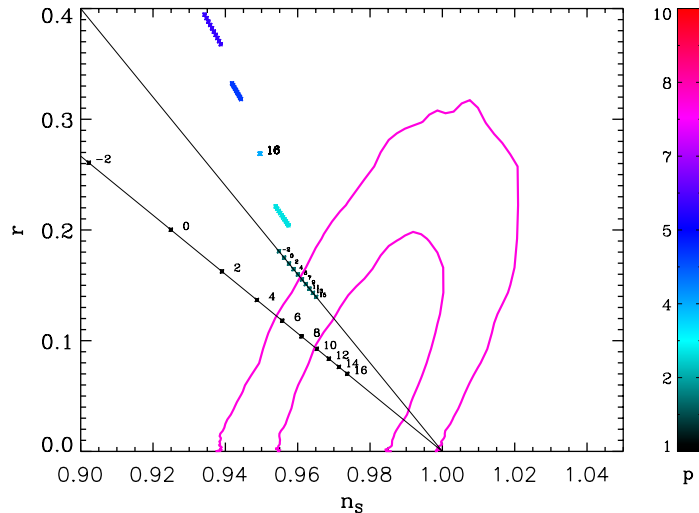


Fig. 1. One and two- σ WMAP confidence intervals in the (n_s, r) plane. Quoted numbers indicate the reheating temperature in the form $T_{\text{reh}} = 10^\# g_*^{-1/4} \text{GeV}$ for various values of the scalar field power p in the potential (lines are for $p \gtrsim 1$ and $p = 2$). See Martin & Ringeval (2010), from which this figure is taken, for details.

its true minimum. The reheating phase duration affects the observational range of scales at which one observes the end of the slow-roll phase. Measurements of the spectral index n_s and the tensor-to-scalar ratio r thus constrain this phase characteristics (equation of state, duration and hence temperature). Fig. 1, taken from Martin & Ringeval (2010), illustrates this point in the case of large field models, for which the potential takes the form $V \propto \varphi^p$.

3 GUT and cosmic defects

Another direct consequence of high energy theories comes straight from GUT, and those are topological defects (Vilenkin & Shellard 2000) and cosmic strings in particular, whose formation is almost inevitable in most cosmologically consistent models (Jeannerot et al. 2003).

If one considers cosmic string contribution to the CMB as a viable source of cosmological perturbations, one rapidly finds that it cannot be made, by itself, to fit the currently available data; this is due, in particular, to the fact that defects are active seeds, and hence cannot produce a coherent spectrum. In other words, the observed acoustic oscillations in the resulting spectrum would be damped. Fig. 2 shows a typical spectrum due to cosmic strings, as calculated e.g. by Ringeval (2010): those can merely be part of the final spectrum, although for some values of the parameters, it is seen that there exists a (small) multipole window for which they might actually dominate the signal.

As a source of cosmological perturbations, strings would also produce non gaussianities in a way that is sufficiently different from the inflation case to be distinguished (Ringeval 2010). It can be argued that forthcoming data have a large potential to exhibit such a string signal: that would be a direct measurement of the GUT symmetry breaking energy scale!

4 Bounces

As we have seen, the now standard inflationary paradigm can be modified by inclusion of topological defects. However, the fact that this mechanism is the best currently available to fit all the data doesn't mean it is unique. In fact, a reasonable way to test its effectiveness would be to find a challenger, and possibly confirm or rule it out. This is what happened to cosmic strings, so the question can be asked as to whether there does exist any plausible contender? It turns out there can be: the bouncing scenario.

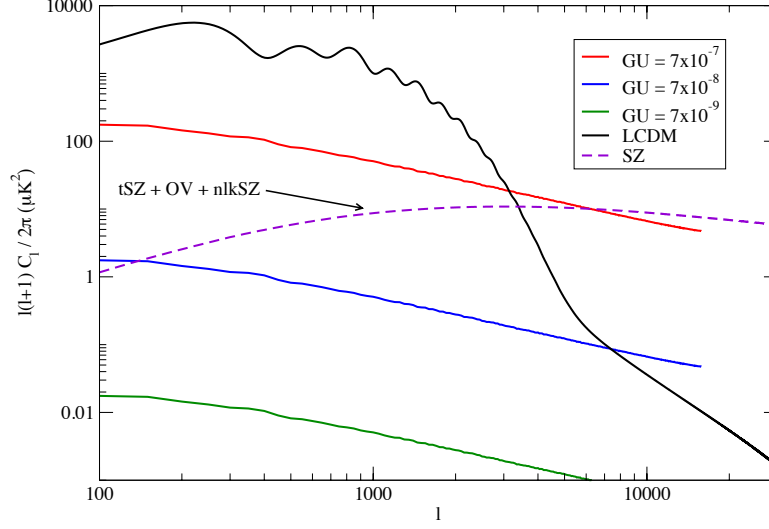


Fig. 2. Multipole spectrum for the standard Λ CDM model – best fit to the currently available data (Komatsu 2010) – and for a network of cosmic strings for different values of the energy per unit length U in units of the Planck mass squared. The dashed curve represents the contribution from the Sunyaev-Zeldovich effects, namely thermal (tSZ), Ostriker-Vichniak (OV) and nonlinear kinetic (nlkSZ). From Ringeval (2010)

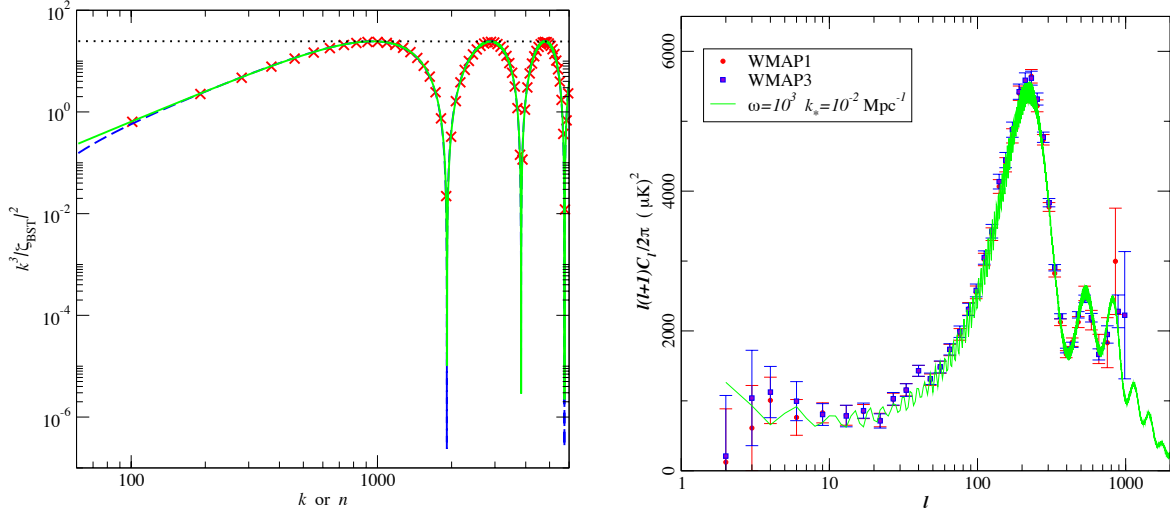


Fig. 3. The primordial spectrum $k^3|\zeta_{\text{BST}}|^2$ (right) and subsequent multipoles C_ℓ (left) for a typical bouncing model. From Falciano et al. (2008)

Instead of using a phase of accelerated ($\ddot{a} > 0$) expansion ($\dot{a} > 0$) as inflation does, having a bounce supposes a phase of decelerated ($\ddot{a} < 0$) contraction ($\dot{a} < 0$). As a result, just before the bounce itself, the total density can be as close to critical as one wishes. With a contraction dynamics dominated by a regular, matter or radiation, fluid, the horizon, being an integral quantity over time (Martin & Peter 2004), can be made to diverge, hence solving this puzzle as well. The remaining usual issues such as homogeneity can be addressed under reasonable additional assumptions (Peter & Pinto-Neto 2008).

Crucial to any cosmologically relevant model is the existence of primordial perturbations which will seed the LSS formation; these can be rather problematic in a bounce model (Peter & Pinto-Neto 2002). It is often said that this category of models faces the difficulty of being very much model dependent which, it is argued, is

not the case of inflation. Not only is this last assertion erroneous, each inflationary model leading to different observational prediction*, but it is also misleading since most bouncing models do also share generic prediction features.

The most important difficulty faced by bouncing models is that classical General Relativity (GR) is very reluctant, under general energy conditions, to let the Hubble rate vanish! Options however can be considered. In the framework of GR, one needs at least a positive spatial curvature and a scalar field (Martin & Peter 2003; Falciano et al. 2008). Still in the classical domain, one can either modify gravity in order to render it non singular (Fabris et al. 2003; Abramo et al. 2010) or consider a fluid that does not satisfy the usual energy conditions (Abramo & Peter 2007; Finelli et al. 2008). Finally, one can use some version of quantum gravity that would apply to the Universe as a whole: these would lead to quantum cosmology models (Peter et al. 2005, 2006, 2007), allowing for a bounce independently of the curvature. In almost all of these models, it turns out that the spectrum of primordial perturbations is modified to include an oscillatory part, that can be compared to observations as exemplified on Fig. 3.

5 Conclusions

Precision cosmology is opening new windows of observations: future data will constrain high energy theories!

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References

- Abramo, L., R. & Peter, P., 2007, JCAP 09, 001.
 Abramo, L., R., Peter, P. & Yasuda, I., 2010, Phys. Rev. D81, 023511.
 Abazajian, K., et al. 2009, Ap. J. S., 182, 543.
 Amanullah, R. et al., 2010, Ap. J. 716, 712.
 Bouchet, F. R., Peter, P., Riazuelo, A. & Sakellariadou, M., 2001, Phys. Rev. D65, 021301.
 Fabris, J. C., Furtado, R. G., Peter, P. & Pinto-Neto, N., 2003, Phys. Rev. D67, 124003.
 Falciano, F. T., Lilley, M. & Peter, P. Phys. Rev. D77, 083513.
 Finelli, F., Peter, P. & Pinto-Neto, N., 2008, Phys. Rev. D77, 103508.
 Fraisse, A. A., Ringeval, C., Spergel D. N. & Bouchet, F. R., 2008, Phys. Rev. D78, 043535.
 Furlanetto, S. R., Peng Oh, S. & Briggs, F. H., 2006, Phys. Rep. 433, 181.
 Jeannerot, R., Rocher, J. & Sakellariadou, M., 2003, Phys. Rev. D68, 103514
 Komatsu, E. et al., 2010, arXiv:1001.4538.
 Martin, J., 2008, Lect. Notes Phys. 738, 193.
 Martin, J., & Peter, P., 2003, Phys. Rev. D68, 103517.
 Martin, J., & Peter, P., 2004, Phys. Rev. Lett. 92, 061301.
 Martin, J. & Ringeval, C., 2001, Phys. Rev. D82, 023511.
 Martin, J., Ringeval, C., Trota, R., 2010 arXiv:1009.4157
 Percival, W. J. et al., 2010, MNRAS 401, 2148.
 Peter, P. & Pinto-Neto, N., 2002, Phys. Rev. D66, 063509.
 Peter, P. & Pinto-Neto, N., 2008, Phys. Rev. D78, 063506.
 Peter, P. Pinho, E., & Pinto-Neto, 2005, JCAP 07, 014.
 Peter, P. Pinho, E., & Pinto-Neto, 2006, Phys. Rev. D73, 104017.
 Peter, P. Pinho, E., & Pinto-Neto, 2007, Phys. Rev. D75, 023516 (2007).
 Peter, P. & Uzan, J.-P., 2009, Primordial Cosmology (Oxford University Press).
 Pogosian, L., Henry Tye, S.-H., Wasserman, I. & Wyman, M., 2009, JCAP 0902, 013.
 Ringeval, C., 2010, arXiv:1005.4842
 Vilenkin, A. & Shellard, E. P. S., 2000, Cosmic Strings and Other Topological Defects (CUP).

*The fact that it is possible to identify a generic “slow-roll” category of inflationary models does not mean these models produce undistinguishable predictions (Martin et al. 2010).